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Comparison of Uniaxial and Biaxial Strengths for Test Pieces with Controlled Flaws

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Indentation cracks are used as controlled flaws in soda-lime glass specimens for failure tests in uniaxial and biaxial loading. The inert strength is independent of loading type within the scatter of data. This result is discussed in relation to the conclusions of other workers who have reported systematic differences in similar comparative tests on specimens containing natural flaws.

Some workers have attempted to compare strength data for brittle materials in uniaxial and biaxial tension.[1–3] Although in each instance the flaw characteristics were similar (i.e. ground surfaces were used), the results are not mutually consistent: two groups working on the same glass ceramic[†] reported differences of up to 25% in strengths for the two stress states, but of opposite sign[1,2]; a third group found the biaxial strength of an alumina material to be lower than the corresponding uniaxial strength, but only by ≈8%.[3] Part of the difficulty in drawing firm conclusions from such studies is the inability to provide complete characterization of the flaws ultimately responsible for failure. A flaw of given size may, by virtue of its geometrical disposition in relation to the applied stress field, experience different levels of stress intensity in uniaxial and biaxial loading[2,3]; indeed, this effect may be sufficient to cause failure from different flaws in the two cases. Separation of mechanical and statistical elements in the accountability of systematic discrepancies is then no longer straightforward. Another contributing factor to the uncertainty in the strength comparisons is the tendency for most workers to apply conventional stress formulas (based on simple beam and plate theory) without independent, experimental calibration; there is growing evidence to suggest that such formulas may, in unfavorable circumstances, be subject to considerable error, particularly in biaxial loading.[4]

This communication describes a simple experiment which provides information on the mechanical response of flaws to uniaxial and biaxial stress states without incurring the described difficulties. The approach involves the introduction of indentation cracks into glass test pieces so that the size, shape, and orientation of the critical flaws can be accurately reproduced from specimen to specimen. An appropriate precalibration procedure is adopted to provide a proper basis for comparative strength determinations.

Flexural test pieces in disk (50 mm in diam., 3 mm thick) and bar (50 by 10 by 3 mm) form were cut from a single sheet of commercial glass plate. The bar edges were beveled and etched with HF to reduce the chance of edge failures. All specimens were annealed at 520°C for 24 h to remove any spurious internal stresses before testing. The bars were tested in four-point loading (inner span 7.5 mm, outer span 30.0 mm), the disks in axisymmetric ring-on-ring loading (inner support diam. 16.0 mm, outer support diam. 39.6 mm). Two dummy specimens of each kind were instrumented with wire strain gages to obtain independent stress evaluations. Complete self consistency between the strain gage outputs and the respective stress formulas for the two loading configurations[5] could be realized by taking a Young's modulus of 70.7±0.8 GPa and a Poisson's ratio of 0.30±0.02.[‡] This latter quantity, which appears only in the biaxial formula, is somewhat higher than generally expected for silicate glasses, suggesting that ideal thin-plate conditions are indeed not being met in this calibration.

For the strength tests, a Vickers pyramid indenter was applied at a load of 5 N to produce a well-defined radial crack pattern at the center of each prospective tensile face.[6–8] All such indentations were made at a hold time of 15 s in air. Care was taken with the bars to align the indenter symmetrically with respect to the edges so that one of the two mutually orthogonal radial crack planes was oriented for maximum flexural tension. To minimize moisture-assisted slow crack growth effects in the strength analysis a drop of silicone oil was placed onto the indentation sites immediately prior to loading and a rapid stressing rate (corresponding to a failure time <1 s) was used.[9] The results obtained for the strengths were: bars (25 specimens) 68±7 MPa; disks (36 specimens) 67±6 MPa.

Thus, within the accuracy of the results, it appears that the response of the radial crack which causes failure is sensitive only to that component of the normal stress perpendicular to the crack plane. Whereas the presence of the second, orthogonal radial crack and of subsurface lateral cracks[10,11] is known to diminish the effective driving force on the primary flaw,[9] the influence of interaction effects is evidently not significantly different in the two stress states. On the other hand, the orientation of the primary flaw relative to the tensile axis can be an important factor in uniaxial loading, where mixed-mode conditions apply.[12,13] A limited test run on bars containing radial cracks oriented at 45° to the tensile axis gave a strength of 80±9 MPa (6 specimens). Thus if the orientation of the critical flaw is subject to a certain degree of arbitrariness one may conclude that uniaxial loading should show a tendency to higher strengths relative to its biaxial counterpart.

Of course, any such conclusions drawn from the present results need to be taken cautiously when predicting the response of materials containing natural flaws. As implied earlier, there are many complicating elements in the determination of general strength properties, including probabilistic factors. Nevertheless, insofar as the indentation crack system can be considered to represent the essential features of flaws in real materials, the approach adopted here allows for definitive characterization of failure mechanics without recourse to statistical analysis.

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‡All errors quoted here are standard deviations obtained from least-squares data fits.

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